BOMEM

NGST

Next Generation Space Telescope

Final Report

Volume 3 - Trade Analyses

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	Function	Name	Signature	Date
Prepared by	Scientist	Louis Moreau		
Prepared by	Scientist	Frédéric Grandmont		
Approved by	Project Manager	André Villemaire		
Approved by	Director, SPR division	Jean Giroux		

BOMEM Inc. • a unit of Elsag Bailey Process Automation N.V.

450 Saint-Jean-Baptiste Avenue • Québec, Québec G2E 5S5 Canada • Phone (418) 877–2944 • Fax (418) 877–2834

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DOCUMENT CHANGE RECORD

Issue	Rev.	Date	Chapter/Paragraph Number, Change Description (and Reasons)
1		12 April 1999	Draft of document
1			First release of document
1	A	13 October 1999	New revision to remove proprietary notices.

1. INTRODUCTION

1.1 BACKGROUND INFORMATION

The Next Generation of Space Telescope (NGST) project of NASA is intended to provide continuity and new focus for research following the success of the Hubble Space Telescope. It is considered to be a technologically challenging project as the technology needed is not necessarily available. It challenges the innovation of the scientific and technological community to come up with an affordable technology to carry out the scientific goals of the mission.

Canada has a strong Space Astronomy community and they have ranked the participation of this project as the priority in their LTSP III submission. In order for Canada to participate, the areas of technical expertise and competence necessarily has to match the required technologies of the NGST project. The nature and scope of the Canadian contribution to the NGST are neither identified nor defined. The CSA sees the Canadian contribution as one that matches the industrial capability, an area that would result in industrial and economic growth and provide a sound base for competitiveness in the international market.

At the end of 1998, CSA awarded a number of contracts to Canadian firms. Bomem was awarded such a contract to study the potential use of a Fourier Transform Imaging Spectrometer as a science instrument for NGST.

1.2 SCOPE OF PROJECT

This work was carried out under contract no 9F007-8-3007/001/SR.

Bomem proposed to study the potential use of a Imaging Fourier Transform Spectrometer as a moderate spectral resolution camera for NGST. The approach was to first investigate the trade space of the instrument design. Next the performance of the instrument was predicted to confirm the suitability of the technology for the NGST mission. The risk analysis and mitigation plans were then completed. Finally the Cost and Schedule estimates were drafted based on the previous findings.

1.3 SCOPE OF DOCUMENT

This document is Volume 3 of the final report. The other deliverables of the study contract are listed in Table 1.

Volume 3 covers the *Trade Analyses* performed on the contribution proposed by Bomem, namely an Imaging Fourier Transform Spectrometer (IFTS) module as one of the central science instrument for NGST. The goal of a trade study is to evaluate the advantages and disadvantages of the various technical options available to implement a component of the system. For example, Fourier Transform Spectrometers can be constructed using flat mirrors or cube-corner retroreflectors. Both of these approaches have advantages and disadvantages. The goal of the flat vs. cube-corner retroreflectors trade study is to find out which is more advantageous for NGST. After the main trade studies are completed a coherent concept for the system, *named a baseline*, appears.

It is important to note however that the trade analyses presented in this volume are first and foremost motivated by the desire to derive an IFTS baseline for the purpose of *cost and schedule estimates*. These trades are only indicative of the type of studies the designers will conduct during the development of this sophisticated spectrometer module. In fact, when a doubt existed in these preliminary trade studies, the choice was motivated by spectrometric performance in the first place, before cost, practicality or maturity of the technology. This may have led to a technical baseline which is more complex and ambitious than usually encountered. This has the consequence of generating a conservative cost and schedule estimate.

Table 1: Deliverables of the study contract

Volume	Document Number	Document	Description
1	SP-BOM-005/99	Executive Summary	5-page summary of the findings of the contract
2	SP-BOM-006/99	Planning Report	Report on the scheduling and cost of the proposed Canadian participation. The planning report also includes the risk assessment and mitigation plan
3	SP-BOM-007/99	Trade Analyses	Report on the trade analyses performed to arrive at a credible baseline for the proposed Canadian participation.
4	SP-BOM-008/99	Performance Analyses	Report on the sensitivity analyses performed to evaluate the suitability of the proposed Canadian participation for NGST
5	SP-BOM-009/99	Technology Report	Report on some proposed novel technology approaches to the specific NGST environment for the proposed Canadian participation.

The trade analyses covered in this document cover the following trade analyses:

- Wavelength coverage, Section 2
- Metrology separation, Section 4
- Two ports vs. Four ports, Section 5
- Corner reflectors vs. Flat mirrors, Section 6
- Spectral bands separation, Section 7
- Sweeping method, Section 8

The radiometric calibration strategy is discussed in Section 9 but due to limited time, no hard conclusion could be reached. NGST poses a substantially different set of conditions from ordinary earth-observing IFTS (where most of the calibration expertise exists) that it is expected that dramatically different calibration approach will be required. Bomem has a unique expertise in design and fabrication of calibration sources and is very interested in this subsystem. However because no baseline could be established, it was decided to leave the calibration sources out of the proposed contribution for the moment.

1.4 REFERENCE DOCUMENTS

RD 1 Bomem Proposal No:SPIR180898, issue 1, revision -, dated 8 September 1998, in response to solicitation No 9F007-8-3007/A.

RD 2 Volume 4 - Performance Analyses NGST performance studies, SP-BOM-008/99

RD 3 Wolf W. L. and G. J. Zissis Ed., The Infrared Handbook, ERIM, 1989.

RD 4 Stockman H. S. & al., Cosmic ray rejection and image processing aboard the next generation space telescope, UCB Astronomy.

RD 5 Handbook of Optics, Volume 1, McGraw Hill, edited by Michael Bass, sponsored by optical society of America, 1995.

1.5 DEFINITIONS

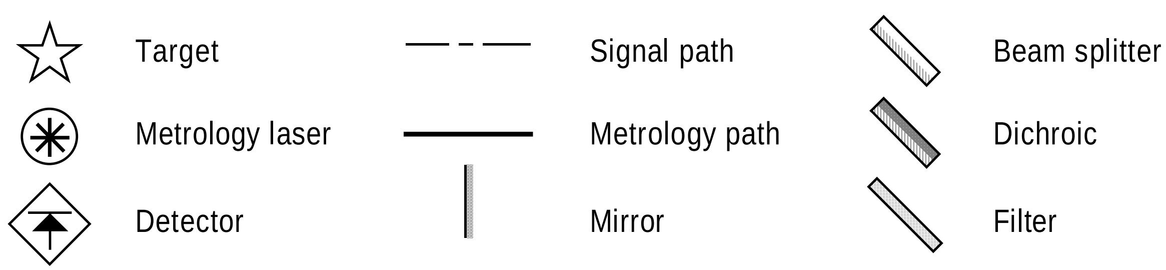
Étendue	The product of the limiting collection area and the solid angle of the limiting field of view. Often called throughput.
Irradiance	Incident radiant energy per unit surface per unit time. Spectral irradiance is the irradiance at a given wavenumber (or wavelength or frequency) per unit wavenumber (or unit wavelength or unit frequency). Usual symbol is *E*.
Jansky	Units of spectral irradiance. Symbol is Jy (1 Jy = 10^{-26} W m^{-2} s).
Radiance	Radiant energy per unit surface per unit solid angle per unit time. Spectral radiance is the radiance at a given wavenumber (or wavelength or frequency) per unit wavenumber (or unit wavelength or unit frequency). Usual symbol is *L*.
Wavenumber	The inverse of the wavelength. Usual symbol is σ (σ =1 /λ).

1.6 ACRONYMS

AC	Alternating Current
CCD	Charge-Coupled Device
CSA	Canadian Space Agency
DC	Direct Current
DF	Dispersive Filter
DFT	Discrete Fourier Transform
DN	Detector Noise
DSI	Double-Sided Interferogram
FFT	Fast-Fourier Transform
FOV	Field Of View
FOV	Field Of View
FPA	Focal Plane Array

FPA	Focal Plane Array
FSR	Free Spectral Range
FTS	Fourier Transform Spectrometer
FTS	Fourier-Transform Spectrometer
FWHM	Full-Width at Half Maximum
IFIRS	Integral Field Infrared Spectrograph
IFS	Integral Field Spectrograph
IFTS	Imaging Fourier Transform Spectrometer
IR	Infrared
MIR	Middle Infrared
MOS	Multi-Object Spectrograph
MPD	Maximum path difference
NEP	Noise Equivalent Power
NESI	Noise Equivalent Spectral Irradiance
NESR	Noise Equivalent Spectral Radiance
NGST	New Generation Space Telescope
NGST	Next Generation Space Telescope
NIR	Near Infrared
OPD	Optical path difference
PN	Photon Noise
RMS	Root-Mean Square
RN	Read-Out Noise
SNR	Signal to Noise Ratio
SNR	Signal to Noise Ratio
SSI	Single-Sided Interferogram
TF	Tuneable Filter
VIS	Visible
ZPD	Zero Path Difference

1.7 LEGEND FOR THE SCHEMATICS



2. GENERAL GUIDELINES

The activity of performing a trade analysis can be summarised as:

1. List all relevant approaches to implement the component or the mode of operation of interest.
2. List the discriminating criteria for each component or the mode of operation. Determine the score of each approach for each criteria in the context of the specific instrument or program.
3. Elect a baseline approach, based on the overall score.

The third step is based on the relative importance of each criteria. There is often insufficient information to determine the relative importance weighting factors and the results are somewhat subjective and lead to discussions. As much as possible the trade studies should be established on quantifiable grounds and associated with engineering studies.

At this early stage in the design of the NGST IFTS we rely on the information available and previous studies. The mission requirements of NGST and the conclusions of RD2 impose the following constraints on the IFTS design:

- The instrument will cover a broad spectral range from visible to MIR.
- The efficiency should be as close to 100% as possible.
- The Etendue should only be limited by the primary telescope and the detector array.
- The instrument must be sensitive to extremely small fluxes in a relatively high noise environment. A SNR of 10 for Irradiance of the order of one nJ is sought.
- A position accuracy of 1% of the step size is sufficient to make sure that the noise caused by position errors is much smaller than the photon noise for small incoming flux.
- Precision and accuracy on absolute radiance output should be close to 1%.
- Calibration should not have to be perform on period shorter than 2 weeks to keep output measurement within 1% stability.
- The observation time required to achieve a high SNR is very long (approx. 12 days) and should not be unnecessarily increased.
- The instrument must be fully space compliant.
- Weight and space should be kept to a minimum.
- The total cost of the design is also limited.

3. WAVELENGTH COVERAGE

Sensitivity range of 1 to 5 micron had been primarily selected for the first definition of the NGST instrument. However, current evolution of the NGST project shows that extended range is becoming a requirement as it is a feature wanted by most end users of the space telescope. Extension of this primary selected wavelength range for NGST operation, must be carefully studied. Any change in the detection range of the instrument spectral coverage could have serious implication on the design and cost. Sensitivity in the visible spectrum (0.4 to 1 micron) and in the MIR (5 to 30 micron) tend to become new targeted characteristics. In this brief discussion, a study for extending the wavelength range is presented.

First, enlarging the instrument waveband means that more than 1 set of detector arrays is needed to collect all the light. The only detectors that cover the full NGST extended waveband are thermal detector and they have non-optimal responsivity to noise ratio as compared to quantum detector. Moreover, it wouldn't be suitable anyway for the following reason. One unfavourable property of Fourier transform spectrometers is that they generate spectra with uniform noise on the spectral scale. This feature tends to promote the breaking up of the full bandwidth into smaller bands where the signal doesn't vary too much in intensity. Otherwise the area of weak signal tend to be drowned by the average noise level caused in part by the high signal area. At this stage it is thought that the spectrum will be covered in 3 slightly overlapping regions (visible, NIR, MIR) forcing the need for 3 separate FPA. As it will be shown in section 6, dichroic beamsplitters are proposed to separate distinct wavebands and direct them on appropriate FPA. Trade studies are also conducted to evaluate the use of separate interferometers instead of using a single one for all waveband. Having separate interferometers is suitable for optimising sensitivity at the desired wavebands but this raise cost somewhat.

At the short end of the wavelength waveband, adding the visible spectrum involves using a different type of detector (probably CCD camera). It also prevent the use of common visible laser for metrology as it would produce a great amount of stray light coinciding with the sensitivity zone of the detector. The absolute calibration of the visible band also brings certain concerns. Calibration source for the visible are much harder to use than the blackbodies used in the thermal IR. Calibration lamps with some kind of scattering mechanism to reduce the intensity will probably have to be developed. Such lamp produces a fair amount of heat that has to be evacuated by proper thermal management system.

At the other end of the spectrum, extension to long wavelength mainly causes problem on stray light control. At such long wavelength (30 μm), insufficiently cooled surfaces show strong emission that could completely mask the target signal. Care must then be taken to cool the instrument enough to reduce the stray light coming from thermal emission of the surroundings. Extending the upper bound from 5 micron to 30 micron could mean having to cool down to temperature close to 20K instead of 80K to reduce stray light contamination. Much more capable cooling system must then be chosen though the spacecraft sunshield should considerably help lower the temperature. The problem mainly consists in evacuating heat generated by electronics, mechanical and calibration devices.

With such a large waveband, spectral separation of metrology become almost impossible, forcing the development of new ideas. Space qualified laser of wavelength lower than 30 μm or higher than 0.4 μm are less common. All these topics are studied in more details in the following sections.

4. METROLOGY SEPARATION

4.1 DESCRIPTION

The metrology system is used to monitor the optical path difference between the two arms of the interferometer. The same metrology signal can also be used to monitor the alignment of the mirrors and instruct an alignment mechanism to correct misalignments. The metrology of FTS instrument is one of the highly desirable components of these instruments as it provides a high fidelity spectral scale by virtue of the frequency standard (laser) used for the interferogram sampling. The metrology makes sure that the system is continuously spectrally stable but the radiation from the metrology signal, usually a laser, can also be a source of pollution as photons from the metrology signal can reach the science detector. This contamination can be particularly important for small flux applications like deep space astronomy where the typical metrology laser can have an energy flux several orders of magnitude higher than the flux of the observed astronomical object. It is thus important to separate the metrology signal from the target signal. In this section, different method of separation is presented and their relative advantages and disadvantages, considering NGST special conditions, are discussed.

The fact that the power of the metrology light should be so much higher that the science light is disturbing at first sight. If the science detector can detect a few photons per second, why would the metrology require, say 10^{15} photons per second? The answer lies in the difference in bandwidth requirement for both systems. The science light interferograms has a very low bandwidth since it requires 10^{5} seconds for an acquisition. The bandwidth of the metrology is much higher. In a simplistic way we can look at the feedback time we expect for the typical tasks assigned to the metrology. In the case of a step-scan system, the most basic task for the metrology is to provide position feedback while moving the interferometer mirror from one fixed OPD position to the next. In order to preserve a good measurement duty cycle we want to minimise the amount of time devoted to transitioning the mirror because no science light is collected. If we want to perform the OPD transition in a few seconds, we need a metrology feedback on the order of few tens to hundred of seconds, which is a much higher bandwidth than the science light. This very large bandwidth admits more noise in the electrical system and thus requires more optical power to achieve adequate position servoing.

4.1.1 No metrology

One of the most radical method, to make sure that the signal from the metrology does not contaminate the signal of the target, is to design a system without metrology. Such a system is spectrally calibrated prior to launch. However, post-launch variations of the spectral calibration cannot be directly monitored. Periodic alignment of the mirrors of the interferometer is also impossible without an interferometric metrology

4.1.2 Temporal separation

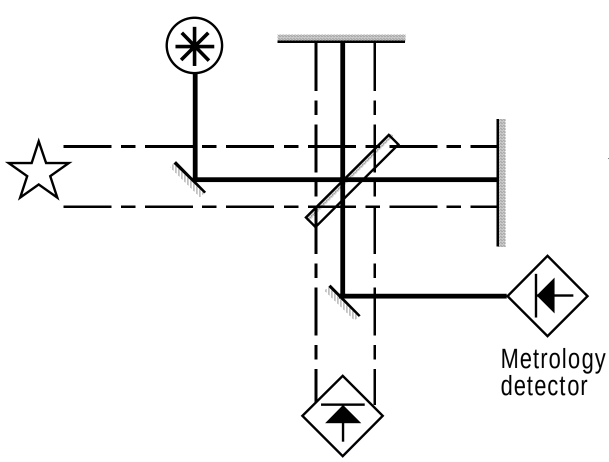
The metrology signal and the target signal can be separated in time. For instance the metrology signal can be on only when the moving mirror is displaced to a new sampling position and off when the target signal acquisition at a given OPD begins. When the metrology signal is off, all the optical elements that were used to direct the metrology signal can be removed from the optical path (potentially at a certain cost in precision) or they can remain in place (potentially causing some obscuration). Since the metrology is off when the acquisition is made, the target signal cannot be contaminated by stray photons from the metrology.

This method is particularly appropriate for a step scan interferometer. During the acquisition, the moving mirror is at rest. The stability of the position can be estimated by comparing the position measurement before and after the acquisition to monitor any drift in position.

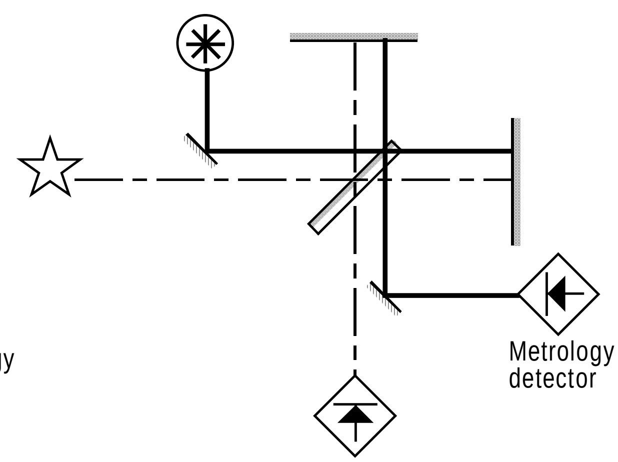
4.1.3 Spatial separation

The metrology signal can be spatially separated from the target signal. In this case, optical elements are positioned in the optical path to make sure that the metrology signal does not reach the detector. The OPD can thus be monitored and the sweep controlled at all time even during the acquisition. These optical elements usually cause some obscuration and block a fraction of the target signal. The metrology signal can be placed off the centre of the optical path (Figure 1 b), reducing or eliminating the obscuration but causing some coupling between tilt errors and OPD position error thus making the alignment and positioning less accurate. An annular separation (Figure 1c) where the metrology signal is all around the target signal can solve that accuracy problem but may results in even larger obscuration.

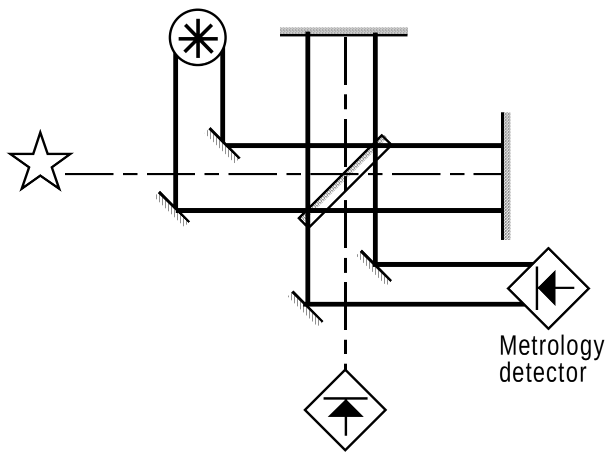
The photon flux from a visible laser with a power of the order of the mW is of the order of 10^{15} photons per second. For signals of the order of a few nJ, the photon flux from the target is only a few photons per second. Even if a small fraction of the metrology signal is deviated by scattering, diffraction, or multiple reflections the contamination can be of several orders of magnitude larger than the signal from the target. Even if we consider only the multiple reflections within the beamsplitter, the photon contamination exceeds the signal of the target by several orders of magnitude (see Annex A).



a)



b)



c)

Figure 1: Metrology spatially separated. a) Centred. b) Off centre c) Annular

4.1.4 Spectral separation

The metrology signal can also be spectrally separated from the signal of the target, by choosing a metrology source with a wavelength outside the waveband of the detector. If the wavelength of the metrology is longer than the longest wavelength of response, it is often believed that the stray light from the metrology will not contaminate the signal and will not increase the photon noise because the detectors are not sensitive to such long wavelength. However because we aim at attenuating the amount of stray light by several order of magnitudes, there is not guarantee that this approach will work. The cut-off (transition to longer wavelength) of semiconductor materials are usually only characterised over a few order of magnitude. Figure 2 shows the relative spectral response of various semiconductor detectors around the cutoff wavelengths. The cutoff of GaN is characterised over four orders of magnitudes while the longer wavelength material is only characterised over two orders of magnitude. Over the very wide dynamic range required for NGST, we expect second order phenomena to take place such as phonon-photon interactions. More investigations are required to conclude on this topic.

If the wavelength of the metrology is shorter than the shortest wavelength of response, stray light from the metrology will not contaminate the signal (in the sense that the target and the metrology are spectrally distinct) but will certainly increase the photon noise. Quantum efficiency at short wavelength decreases somewhat but does not reach zero. Because the photon flux from the metrology is much higher than the photon flux from the target (15 order of magnitude higher in the case of a 1 mW visible laser), even if the quantum efficiency is very low the increase of the photon noise can be significant. For the same reason, high-pass optical filters are probably not a solution. An imperfect filter will not completely remove the stray light from the metrology and may also reduce the transmission efficiency of the target signal.

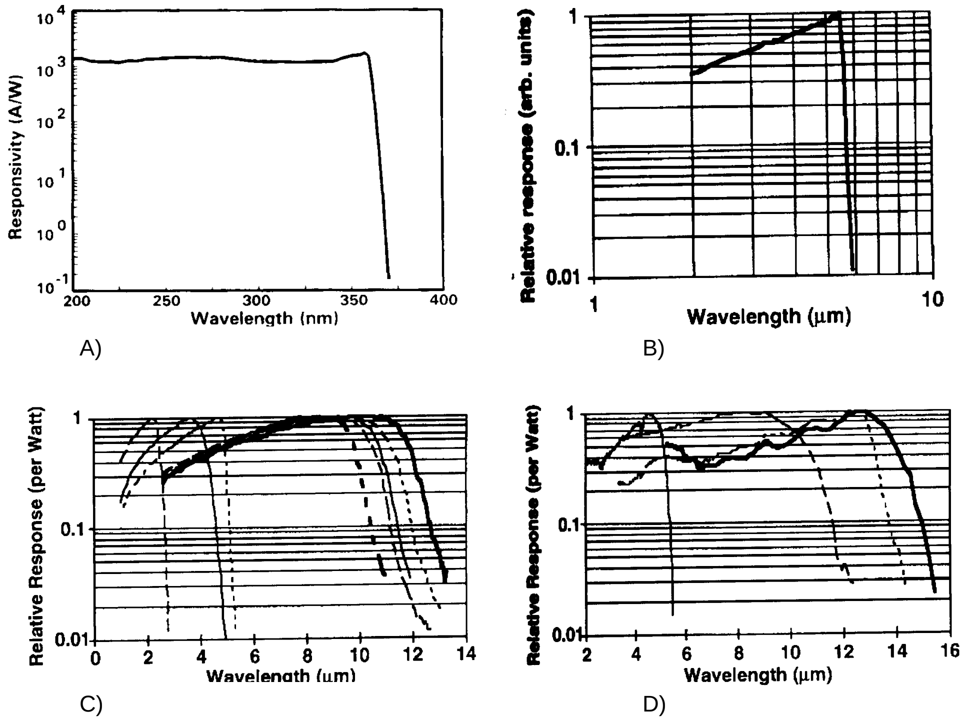


Figure 2: Examples the spectral variation of the relative response per watt (directly related to quantum efficiency times wavelength), for A) GaN photodiode (no AR coating), B) InSb photodiode (no AR coating), C) HgCdTe photodiodes with various cutoff wavelengths (no AR coating), and D) HgCdTe photoconductors with various cutoff wavelengths (with AR coating). Data taken from RD 5

If spectral separation is chosen, some form of spatial separation is also required to inject the metrology signal in the interferometer and direct it to the metrology detectors. The techniques then deals with some of the advantages and disadvantages of spatial separation alternatives (see Section 4.1.3). Spectral separation is merely a way to reduce the contamination of the signal by the metrology. Moreover, spectral separation limits the metrology sources that can be used. If NGST is to be used from the beginning of the visible, around 400 nm, to the thermal infrared, around 30 μm, the choices of metrology sources are drastically limited. There are not many types of lasers available at short wavelengths and most of them, such as Excimer lasers, are unsuited for such operation. At longer wavelengths, the choice of lasers is slightly larger but whether they are suitable or can be space qualified is doubtful. Moreover, at longer wavelengths the period of the reference signal is larger and it may impair the achievement of a fine position resolution.

4.1.5 Indirect metrology

The OPD can also be monitored indirectly. Figure 3 shows an example of such an indirect monitoring. In this example the position of the moving mirror is measured by a second interferometer that uses the back of the moving mirror as one of its reflectors. Since the metrology and the signal from the target go through completely different optical path, the signal is not obscured. Given the extremely high attenuation required to avoid contaminating the signal of the target, care must be exerted so that no light from the metrology source "leaks" from the metrology interferometer to the science interferometer, particularly around the edge of the moving mirror. The process illustrated on Figure 3 is only an example of indirect metrology. There are other possible configurations. For instance an inductive or capacitive sensor can be used to monitor the position of the moving mirror.

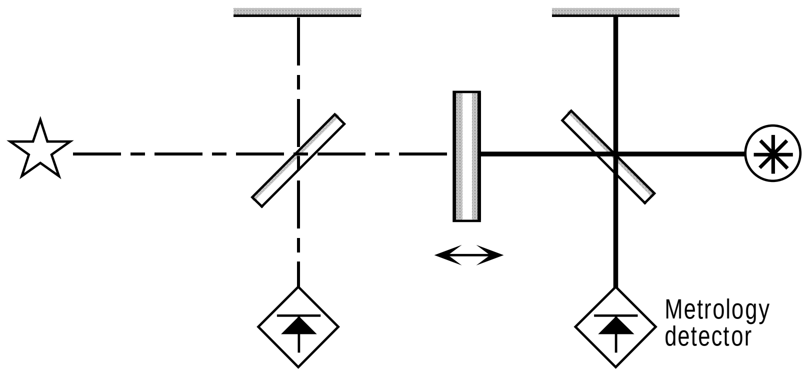


Figure 3: Example of indirect OPD monitoring

4.2 COMPARISONS

Table 2: Qualitative comparison of various metrology configuration

Configuration	Advantages	Disadvantages
a) No metrology.	1. No signal contamination. 2. No obscuration. 3. Simplest design.	1. No position monitoring. 2. No dynamic alignment.
b) Temporal separation.	1. No signal contamination. 2. Metrology can be of any wavelength. 3. Having no obscuration is possible.	1. Position monitoring is not continuous. 2. May require actuators to move the injection and retrieval optics in and off the path (if no obscuration is required).
c) Spectral separation.	1. Constant monitoring. 2. No signal contamination if longer wavelength is used.	1. Difficult to realise if NGST is to measure from UV to TIR. 2. May increase the photon noise if the wavelength of the metrology is shorter than the lower wavelength of the band. 3. Not as precise monitoring if a

		long wavelength is used. 4. Must be used with a spatial separation alternatives.
d) Spatial separation: centred.	1. Constant monitoring. 2. Metrology can be of any wavelength.	1. Potential signal contamination caused by scattering, multi-reflections and diffraction. 2. Obscuration.
e) Spatial separation: off centre.	1. Constant monitoring. 2. No or small obscuration. 3. Metrology can be of any wavelength.	1. Potential signal contamination caused by scattering, multi-reflections and diffraction. 2. Some coupling between OPD errors and tilt errors.
f) Spatial separation: annular.	1. Constant monitoring. 2. No or small obscuration. 3. Metrology can be of any wavelength.	1. Potential signal contamination caused by scattering, multi-reflections and diffraction.
g) Indirect	1. Signal contamination can be prevented. 2. No obscuration. 3. Simultaneous observations. 4. Metrology can be of any wavelength.	1. Does not monitor the position directly (e.g. sensitive to differential thermal distortion). 2. More complex design.

4.3 CONCLUSIONS

The question of contamination is a serious one which dismiss option c), d), e) and f). Solution a) does not provide true OPD or alignment monitoring capabilities and is, thus, less interesting. The temporal separation does not have such problems. The worst limitation of that option is the lack of information while the metrology is off. Whether such a system can work and allow a reliable monitoring of the position and the alignment remains to be seen. The accuracy may depend on the sweeping method used; this option is probably more suited to a step scan sweep than a continuous sweep. Breadboarding activities is a very good approach at mitigating this risk.

Option g) on the other hand present some interesting features. Even if it does not provide true OPD, the deviation from real values can be strongly minimised by controlling the environment temperature which will certainly be the case in NGST instrument environment. This option also allows some form of indirect alignment monitoring. However, it would be risky to think of this option as a stand alone option for providing metrology for the instrument as the metrology signal does not run through all optical elements to account for misalignment or OPD.

Temporal separation seems to be the most appropriate option for NGST and it worth being tested and investigated further. This is the method chosen for this baseline instrument but hybrid version of option b) and g) might become handy in solving some of the problems associated with temporal separation.

5. TWO PORTS VS. FOUR PORTS

5.1 DESCRIPTION

Every Michelson interferometers and its derivatives have two input ports and two output ports. However, for the most common implementation of the Michelson interferometers, the second output port is superposed to the first input port (returning 50% of the incoming light back to the target) and the second input port is superposed to the first output port (see Figure 5b). With such interferometers, the second output port cannot be directed to a detector without blocking the signal from the target and the second input port is occupied by the detector, making them, for all practical purposes, two ports interferometers.

There exists a few ways to make the four ports available. Two such ways are shown on Figure 4, one using cube corner mirrors and one using flat mirrors. The first method separates the beam in the system pupil, while the second method separates the beam in a system field image. In both cases, the second output port can be occupied by a second detector. This is equivalent to doubling the efficiency of the interferometer, thus increasing the signal to noise ratio by a factor $\sqrt{2}$. Comparing the signal from the first detector with the signal from the second detector may also allow the detection and correction of soft failures due to cosmic rays. In this dual port configuration, light coming from the second input must be controlled as it is added to the first input. This input will have to be blocked by a cold stop or it could be used to estimate the background radiation.

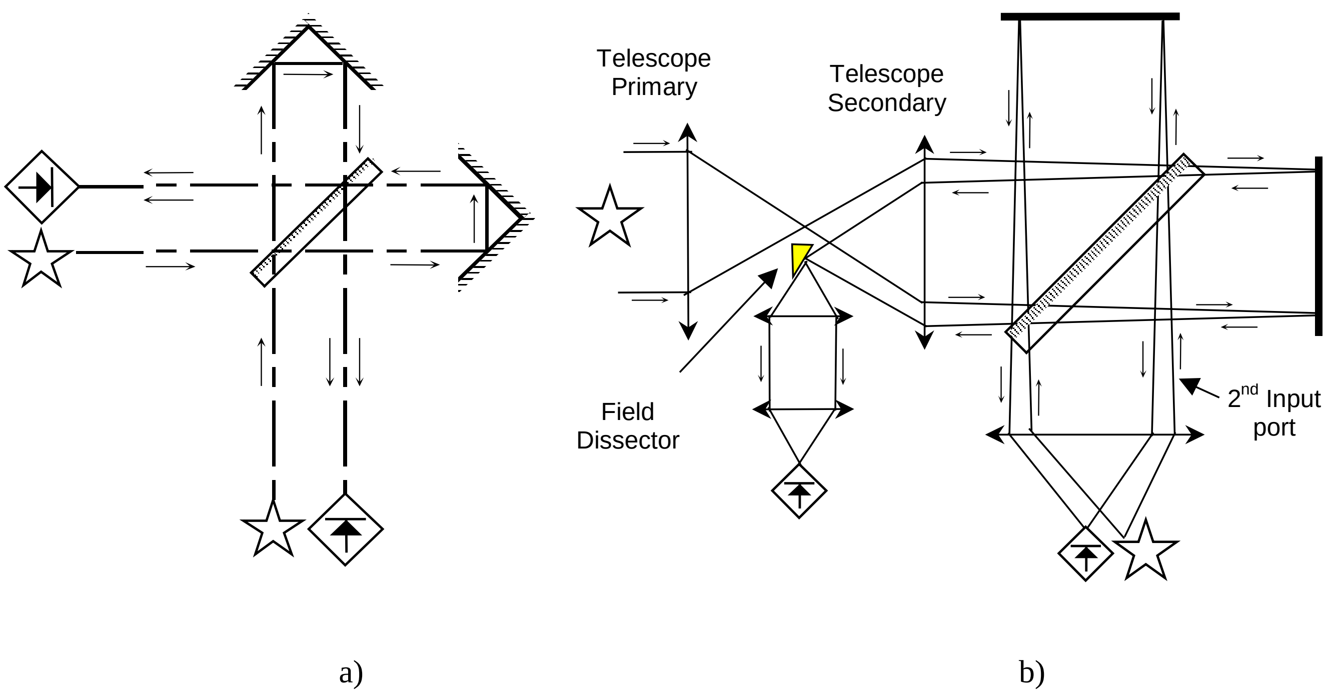


Figure 4: Two examples of a four ports interferometer a) with corner reflectors b) with flat mirrors

No matter if the interferometer has two or four distinct ports, the principle is similar. The beam incident from the left input hits the beamsplitter where it is divided into reflected and transmitted wavefronts. These wavefronts are reflected back to the beamsplitter (acting as a recombiner) by the interferometer mirrors, to recombine and interfere. Due to the nature of the beamsplitter, two such recombinations are obtained, one reflected and one transmitted. In fact, the interferometer can be seen as a sinusoidal chopper with a certain modulation frequency that depends on the wavelength of the light. The light is not destroyed but rather switched from one output port to the other.

5.2 COMPARISONS

Table 3: Qualitative comparison of the single and dual port configuration

Configuration	Advantages	Disadvantages
a) Two ports	1. Requires only one set of detectors. 2. Simpler design. Lower cost.	1. Lower efficiency.
b) Four ports	1. Increase the SNR by a factor $\sqrt{2}$. 2. Redundancy. 3. Simultaneous measurements with two detectors make the correction of glitches and spikes easier.	1. Requires two sets of detectors. 2. More complicated design. Higher cost.

5.3 CONCLUSIONS

As mentioned in RD 2, NGST will requires the highest efficiency possible to achieve a high SNR for small incoming flux. This reason alone is sufficient to justify the selection of the four-port option over the two-port option.

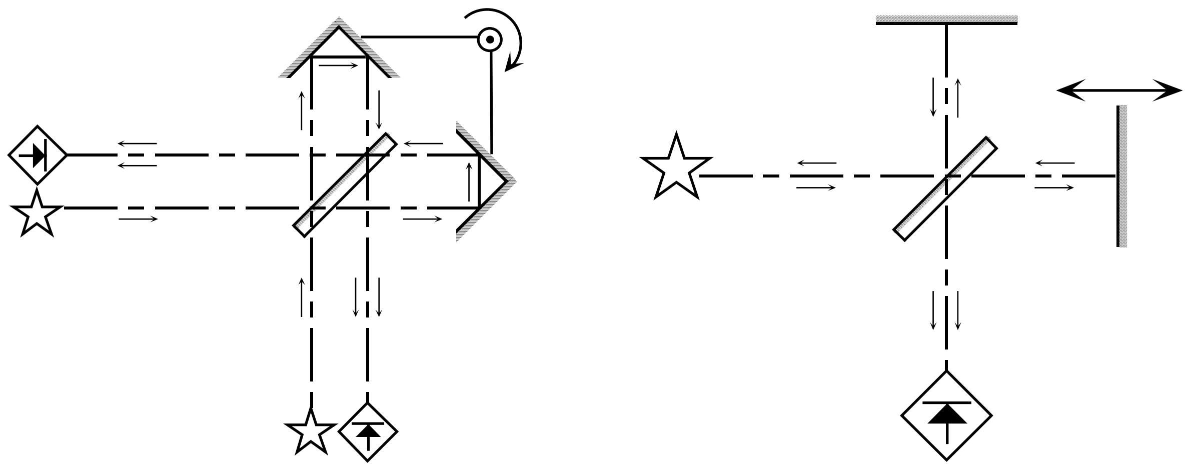
From the point of view of the interferometer, the four-port configuration is only marginally more expensive than the two-port configuration. Obviously, the same thing cannot be said for the detector subsystem, as the four-port configuration implies a duplication of that subsystem. For the purpose of evaluating the feasibility, cost and schedule of the interferometer module of NGST, we will use the four-port configuration, so as to consider the worst case.

6. CORNER REFLECTORS VS. FLAT MIRRORS

6.1 DESCRIPTION

Most of today's Fourier transform spectrometer (FTS) are still based on the interferometer designed by Michelson and Morlay in the early 20th century and shown on Figure 5b. These FTS use flat mirrors. One notable exception is the retroreflector spectrometer marketed by Bomem and Brucker, such as the cube corner interferometer shown on Figure 5a. With the flat mirror configuration, the optical path of one of the interferometer arm is usually changed by moving one mirror. With the Bomem MB interferometer, a system with a corner cube configuration, an optical path difference between the two arms is achieved by rotating the two retroreflectors around a central pivot.

Both configuration has its advantages and disadvantages. A partial list of these characteristics is given in Table 4.



a) b)

Figure 5: a) Interferometer with corner reflectors. b) Interferometer with flat mirrors.

6.2 COMPARISONS

Table 4: Qualitative comparison of the flat mirrors and corner reflectors configuration

Configuration	Advantages	Disadvantages
a) Corner reflectors	1. Only small residual tilt error. 2. Easier to construct a passive mechanism.	1. Lower ultimate modulation efficiency. 2. Possible shear error. 3. Three reflections: reduced transmission efficiency. 4. Composite assembly with cemented parts; fragility & stability concerns.
b) Flat mirrors	1. Better ultimate modulation efficiency. (No shear error) 2. Better transmission. (Only one reflection) 3. Robust monolithic component.	1. Possible tilt error. 2. Good alignment requires a dynamic alignment system.

6.3 CONCLUSIONS

Because of the stringent sensitivity requirement of NGST we will consider a dynamically aligned flat mirror interferometer design. This option is more apt to produce the highest interferometer efficiency as it potentially has a higher transmission efficiency and higher modulation efficiency than the configuration with corner reflectors.

7. SPECTRAL BANDS SEPARATION

7.1 DESCRIPTION

Given the sensitivity requirement of NGST and its missions, it will probably be a multi-detector system. Each detector need to be optimised for a given spectral band. Most proposed designs suggest at least two spectral bands: one from 1 to 5 μm and another from 5 to 10 μm. Other spectral bands to extend NGST's capabilities in the visible as well as at longer wavelengths (up to 30 μm) are also considered.

Several design options are possible to separate the incoming radiation in spectral bands and direct each band to the appropriate detector. Figure 9 shows six different configurations to spectrally separate the radiation incoming from the target. The first two designs (a and b) use a moving mirror to direct the radiation to every detector in succession, either before or after the interferometer. Acquisition is first performed in the first spectral band, then the mirror is moved to direct the radiation to second detector and so on. The next two designs (c and d) use a reflecting prism to split the incoming radiation in different parts and direct each fraction to a different detector. The last two designs (e and f) use a series of dichroic beamsplitters to separate the incoming radiation in several spectral bands and direct each band to a given detector. A dichroic beamsplitters is an optical component with a coating designed to be highly reflective in a specific spectral band and highly transparent at other wavelengths.

Regardless of the exact method used to spectrally separate the incoming radiation, the separation can be done before the signal enters the interferometer or after it exits the interferometer. If the separation is done after the signal exits, the beamsplitter of the interferometer will have to be designed so as to be effective over the total waveband used by NGST. It is difficult to design a good wideband beamsplitter for various reasons. A typical beamsplitter is usually made of three different parts with different functions: the reflective coating, the bulk substrate, and the anti-reflection coating. The reflective coating is used to split the incoming beam in a reflected and a transmitted part, ideally in equal proportion. The bulk substrate is a thick piece of transparent material to support the reflective and anti-reflection coatings. The anti-reflection coating is used to minimise the reflectance at the second interface of the beamsplitter. These three parts are made of various dielectric materials (often several layers of such materials for the coatings) that are not necessarily effective at all wavelengths. For instance most materials that are transparent in the near-IR have a low transmittance in the visible and the middle-IR (see Figure 7 for a few examples).

Moreover, it is very difficult to design coatings that are effective over a broad range of wavelengths; these coatings are based on constructive or destructive interference and so, the effects are strongly wavelength dependent. To further complicate the matter, the surface roughness of the material used in the infrared tends to be important compared to the wavelengths in the visible. Figure 8 shows the modulation efficiency considering no wavefront deformations (i.e. equal to four times the product of the beamsplitter transmittance and reflectance) of the reflective side of an extended range caesium iodine (CsI) beamsplitter optimised for the near-infrared.

The difficulty of making a wideband beamsplitter is well illustrated with the CsI example. CsI is one infrared material best transmission range in the long wave (see Figure 7). However, being a alkaline salt, it is a very soft material so it is very difficult to polish flat enough for a good modulation efficiency in the short wave.

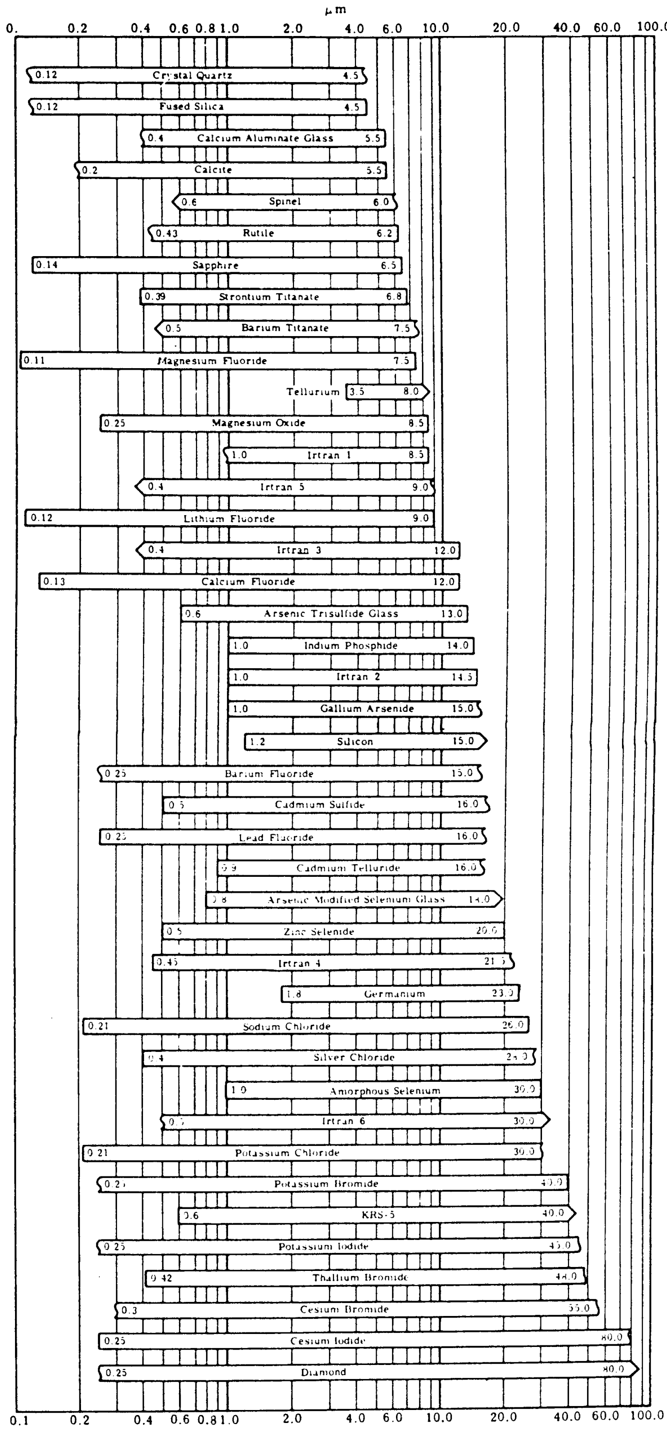


Figure 6: Transmission region (from 100 to 10%) of various optical materials with a thickness of 2mm (RD 3).

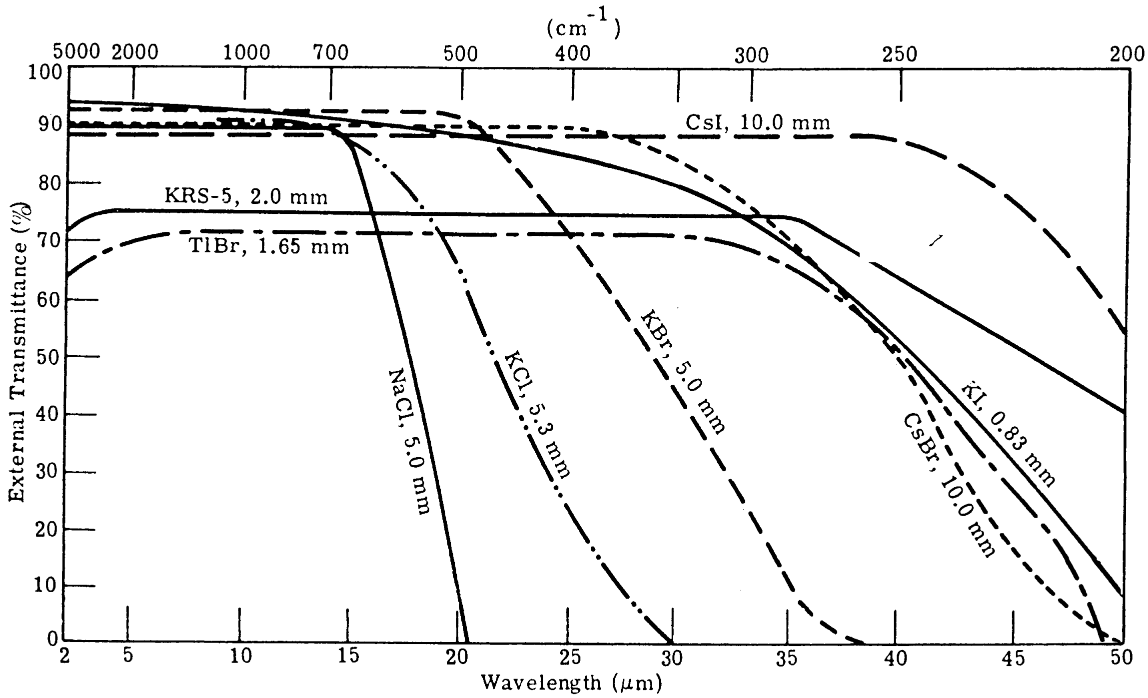


Figure 7: The spectral transmittance of caesium iodine, potassium iodine, potassium bromide, thallium bromide, KRS-5, caesium bromide, sodium chloride, and potassium chloride (RD 3) .

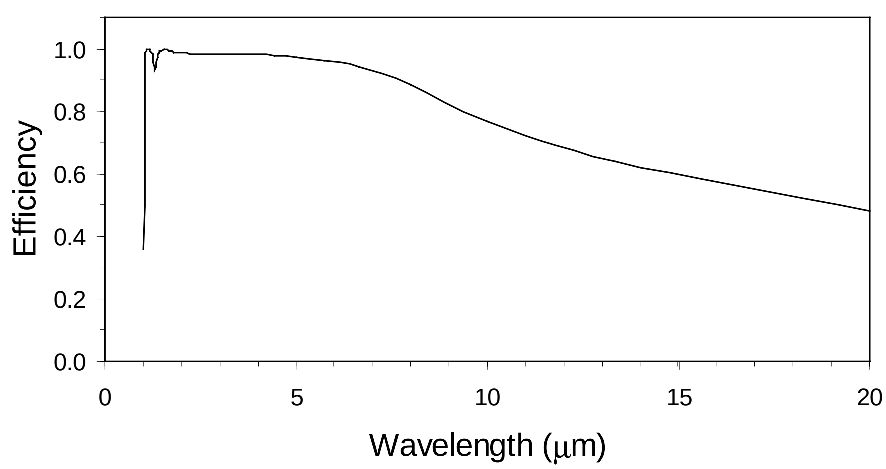


Figure 8: Modulation efficiency at angle of incidence of 30º for extended range NIR-MidIR CsI beamsplitter.

On the other hand, if the separation is made before the signal enter the interferogram, each spectral band will be directed to a different interferometer. Each beamsplitter can then be optimised for that particular narrower band. Of course, that second option is more costly and take up more space and weight. At this point, we will put sensitivity ahead of the cost, and adopt a split before the interferometers in order to have several optimised interferometer

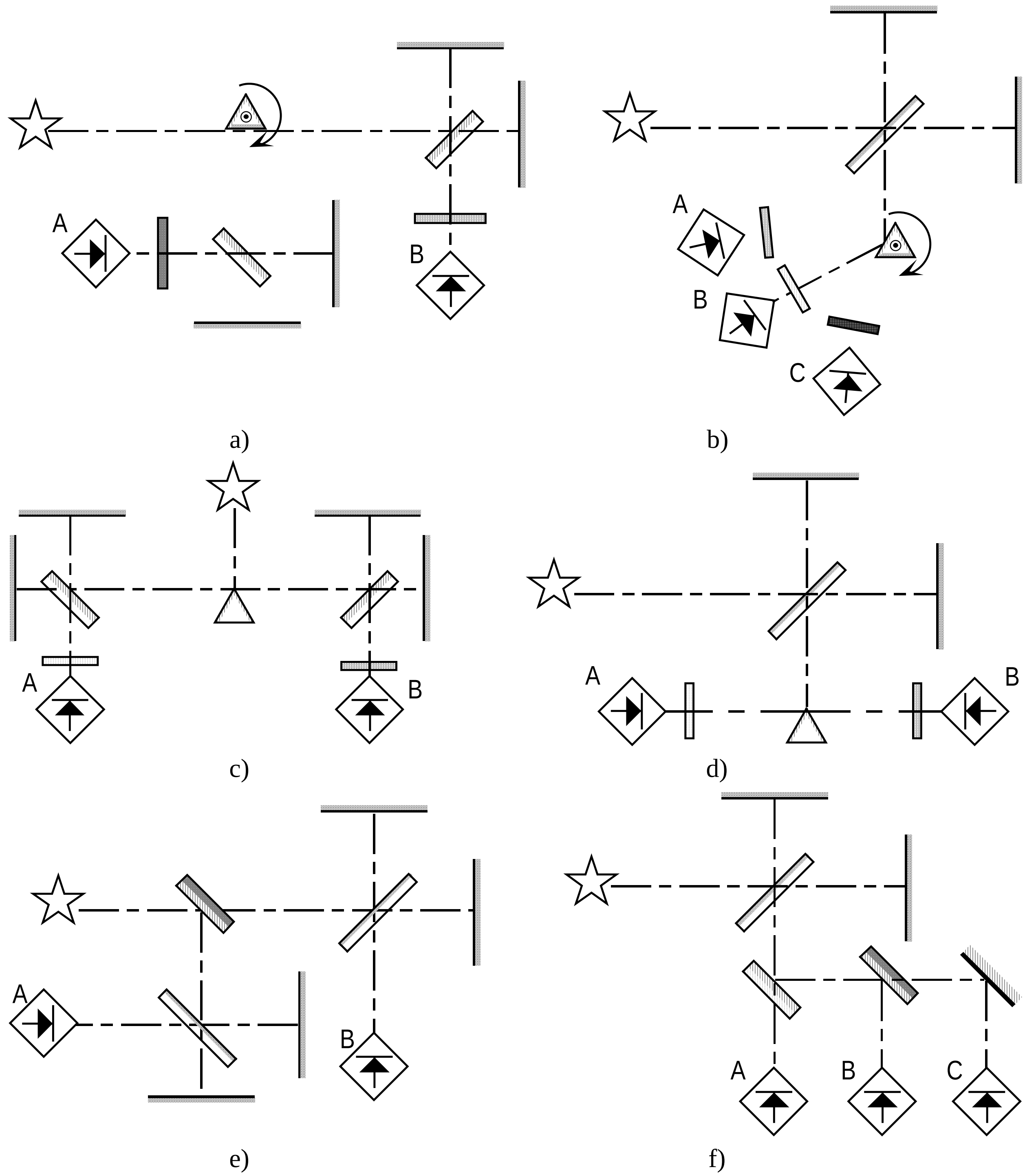


Figure 9: Example of band separations. a) Pointing mirror at the entrance. b) Pointing mirror at the exit. c) Wedge at the entrance. d) Wedge at the exit. e) Dichroic beamsplitters at the entrance. f) Dichroic beamsplitters at the exit.

7.2 COMPARISONS

Table 5: Qualitative comparison of various band separation configurations

Configuration	Advantages	Disadvantages
a) Pointing mirror at the entrance	1. Small transmission loss. 2. The beamsplitters can be optimised for each band. 3. Can accommodate several bands. 4. Less components.	1. Non-continuous operation – longer observation time. 2. Requires one interferometer per band (increased cost and weight). 3. Moving parts. 4. Differential polarisation effects.
b) Pointing mirror at the exit	1. Small transmission loss. 2. Can accommodate several bands.	1. Non-continuous operation – longer observation time. 2. Requires a broadband beamsplitter. 3. Moving parts. 4. Differential polarisation effects.
c) Reflective prism at the entrance. (field separation)	1. The beamsplitters can be optimised for each band. 2. Simultaneous observations.	1. Transmission efficiency is divided by the number of prism faces. 2. Requires one interferometer per band (increased cost and weight).
d) Reflective prism at the exit (field separation).	1. Simultaneous observations.	1. Requires a broadband beamsplitter. 2. Transmission efficiency is divided by the number of prism faces.
e) Reflective prism at the entrance. (pupil separa-tion)	1. The beamsplitters can be optimised for each band. 2. Simultaneous observations.	1. Each detector sees a slightly different field of view. 2. Require a larger primary telescope to achieve the same FOV size.
f) Reflective prism at the exit. (pupil separation)	1. Simultaneous observations.	1. Requires a broadband beamsplitter. 2. Each detector sees a slightly

		different field of view. 3. Require a larger primary telescope to achieve the same FOV size.
g) Dichroic at the entrance	1. The beamsplitters can be optimised for each band. 2. Can accommodate several bands. 3. Simultaneous observations.	1. Transmission loss due to imperfect dichroic beamsplitters. 2. Requires one interferometer per band (increased cost and weight).
h) Dichroic at the exit	1. Simultaneous observations. 2. Can accommodate several bands.	1. Requires a broadband beamsplitter. 2. Transmission loss due to imperfect dichroic beamsplitters.

7.3 CONCLUSIONS

Since it is difficult to design a beamsplitter efficient over a wide spectral range and a high efficiency is required to obtain a good enough SNR for the small flux of expected NGST's targets, the options that requires a broadband beamsplitter should be rejected. In other words, the spectral separation should be performed at the entrance of the instrument and every band directed to a different interferometer optimised for that particular band. Spectral separation before the instrument also allows to optimise sweeping patterns, stroke and speed for each band but it necessarily implies higher cost and larger weight and space.

The total acquisition time required to achieve a good SNR is already very long, of the order of 10 days (see RD 2). For that reason the configuration using a pointing mirror should also be rejected because it does not allow simultaneous observation.

The remaining design options are c), e) and g). A high efficiency cannot be achieved with option c). Using option e) will result in smaller FOV unless a larger primary telescope is used. Since the primary telescope is already a very challenging and costly component of NGST, it is doubtful that its planned diameter can be increased further. If the FOV seen by every detector array is smaller, the total time required to cover a given portion of the sky will be larger. because of these two factors, option e) is not interesting. The remaining option is g): separating the various spectral bands with a series of dichroic at the entrance of the sensor. Although this option is not ideal in terms of transmission efficiency, cost, weight and power consumption it is the best compromise.

8. SWEEPING METHOD

8.1 DESCRIPTION

Three main sweeping methods may be considered.

Step scan: The interferometer mirror is moved from one OPD position to another by monitoring the metrology signal. Once the correct sampling position is found, the system is stopped. The detector is then exposed to light from the target. The system keeps on running through this sequence until the maximum path difference is reached. Output gives only one interferogram per sweep.

Continuous scan: (- 1 sweep - Low speed) The speed of OPD variation is servo-controlled at a constant low value. The integration of the detector occurs while the mirror is moving. Only one sweep is needed to conclude measurement. Multiple interlaced interferograms may be acquired in one sweep.

Continuous scan: (- multiple sweeps - High speed) The speed of OPD variation is servo-controlled at a constant high value. The integration of the detector occurs while the mirror is moving. Multiple sweeps are needed to conclude measurement and achieve the required SNR. Each sweep leads to one or more interferogram.

Figure [10] shows the evolution of the moving mirror as a function of time for all three techniques. The number of steps and the OPD range have been reduced on the graph to highlight the aspect of various sweep method. The number of sweep for the high speed continuous scan is for illustration only.

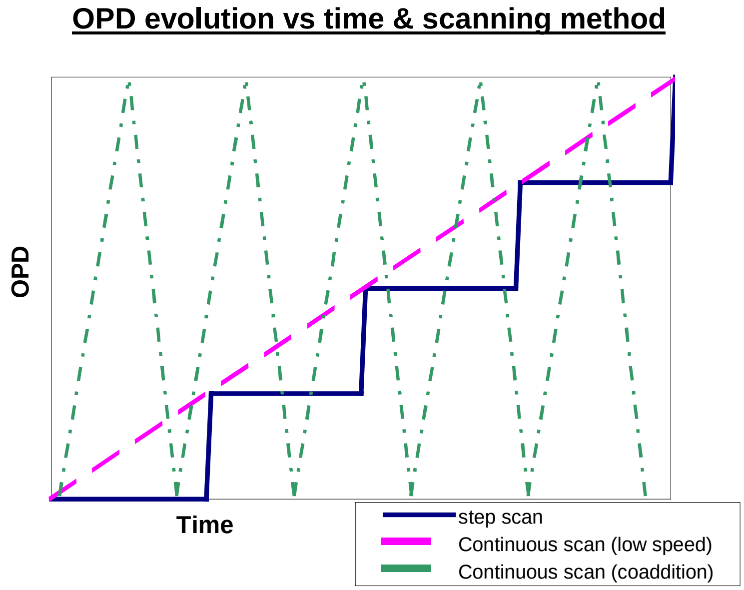


Figure 10: Sweeping methods studied

Regardless of the techniques chosen, one will have to integrate light from the target over similar periods of time to achieve the required SNR since a minimal number of photon (and hence time) must be received from the source. Typical integration time for a complete acquisition is of the order of 10^6 seconds ($2X10^6$ s. = 23.2 days in our RD2 example) to achieve reasonable SNR for incoming flux of the order of 10^{-9} Jy as mentioned in RD2. Therefore, the stop and stare approach (step scan) is worth considering as it is normally rejected for faster acquisition system because of its inefficient duty cycle.

The duty cycle of the step scan method is known to present some inefficiency partly because no acquisition occurs while the system is positioning itself to the next sampling position. However in a system driven by conclusions of RD2, assuming that single sided interferogram are acquired, 100 sampling positions would be needed to complete the overall time of $2X10^6$ with R=100, leading to individual step of $2X10^4$ second (5.5 hours). With such long integration, it is believed that the transit time (likely to be of the order of one second) will represent less than 0.01 % of the total integration time removing the argument of inefficiency. Also, one of the greatest advantage of this technique is that it is fully compatible with temporal separation of metrology since it may be possible to not monitor the OPD when it is stationary. On the other hand having to keep a mirror stable over such long acquisition time presents a challenge that may be addressed by using a hybrid metrology system (temporal and indirect metrology) and proper positioning device.

If the second method is chosen, a sensitive servoing mechanism will have to be designed. For example, let us calculate the speed needed in our RD2 case study. The total optical path difference needed to achieve the stated 80 cm^{-1} spectral resolution can be calculated by the following relation:

$$Resolution\,in\,wavenumber \approx \frac{1}{Total\,OPD}$$

$$80\,cm^{-1} = \frac{1}{Total\,OPD} \rightarrow Total\,OPD = 0.0125\,cm$$

Assuming that the interferometer used has 2:1 optical vs mechanical movement ratio, the total travel of the moving mirror corresponding to a MPD of 0.0125 cm, is 62 µm. One will have to servo the movement of the moving mirror to a speed of 1.88 nm/min to conduct a single sweep in $2X10^6$ seconds. Different metrology design have already been studied to provide sufficient feedback to servo control loop to accomplish such a task.

At this speed the interferogram smear caused by mirror movement during acquisition can be minimised by using shorter individual integration time. In this second method, a series of N interlaced interferograms would be acquired during a single sweep, each having the same sampling interval Δx but being spaced apart by $\Delta x/N$. At the end of the sweep, the N spectra derived from the N interferograms can be averaged, increasing the SNR by a factor $N^{0.5}$. The advantage is that the camera is acquiring at every instant of the total measurement time and lead to a perfect duty cycle efficiency.

For the second continuous scan variant, which is the technique used in most Bomem instruments, the velocity is higher and several sweeps (say N) are used to read the interferogram. The N interferograms acquired are then averaged, also increasing the SNR by a factor $N^{0.5}$. Smearing effect can be more important with this method if no interlaced interferograms are acquired during each sweep. Doing so would however increase the processing power needed as well as the amount of data storage space.

To carefully study the individual aspects of each method, an important fact has to be considered. The conclusions of RD4 indicate that some limits have to be considered relative to the integration time used in the NGST instrument. A too short integration time gives too few photons compared to the readout noise which is a constant for readout operation. On the other hand, an integration time too long makes it impossible to determine the flux because ionising cosmic event that change detector count (see Figure [11]). One way to readout rapidly (to avoid cosmic spikes) while minimising the readout noise is to perform successive non-destructive readout cycles. For the case of NGST, an integration time of 10^3 seconds with 64 non-destructive readouts is assumed to be an optimised way of sampling the science signal. This not only reduces the total effective readout noise well below the background noise, but it also permits the detection and removal of cosmic ray event (reference RD4). Figure 11 shows the aspect of a typical acquisition. A slope fitting algorithm where cosmic ray jump can easily be removed, is used to evaluate the incoming flux which correspond to the slope on the graph. It is important to note that this 10^3 integration time lead to only one point on the interferogram as one flux measurement is extracted from the graph. Also note that any offset is remove automatically with this method. In fact the slope extract operation removes some of the 1/f noise problems usually associated with DC measurements.

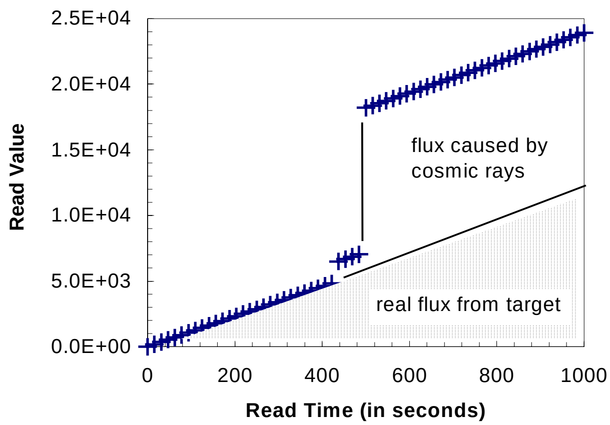


Figure 11: Example of non-destructive readout in presence of cosmic events

This conclusion sets a constraint on the different sweeping alternatives studied. For the step scan technique, it means that several acquisitions will be collected at every sampling position. In our example where the step integration time is of 2X104 seconds, 20 acquisitions of 103 seconds could take place at each of the 100 sampling positions. It also mean that 20 interlaced interferogram would be collected if the second method was used. The third sweeping method is slightly handicapped by this time constraint. If only one data can be pulled out of the algorithm every 103 second, one can't think about having a very fast multiple sweep sequence. For a 100 point interferogram, this would lead to a minimum time for a complete sweep of 100 X 103 seconds = 105 seconds, close to the 2X106 required for the complete measurement. Then 20 interferograms could be obtained in the total integration time, increasing the SNR by a factor of 200.5 = 4.47, a result similar to the one obtained with the second method.

8.2 COMPARISONS

Table 6: Qualitative comparison of various sweeping methods

Configuration	Advantages	Disadvantages
a) Step scan	1. Optimal modulation at fixed OPD. 2. Easy to use with temporal separation of metrology 3. Lower processing power needed. 4. Minimal storage space.	1. Duty cycle inefficiency; transit time is lost. 2. 1/f noise may couple to spectra.
b) 1 scan at low velocity	1. Best duty cycle.	1. Modulation may be limited by interferogram smear during integration. 2. High storage space required. 3. 1/f noise may couple to spectra. 4. Not easy to use with temporal separation of the metrology.
c) Continuous scan with coaddition	1. 1/f noise rejection.	1. Modulation limited by interferogram smear during integration. 2. High storage space required. 3. Not easy to use with temporal separation of the metrology.

8.3 CONCLUSIONS

All three method may show similar SNR performance in operating conditions like the NGST environment. The step scan has some duty cycle inefficiency, but the two others are suffering from smear as they integrate while the output signal is changing. It is not obvious however that this smearing effect has a dramatic influence over the quality of the measurement obtained since the calibration of the instrument will account for this behaviour.

On the other hand, in Section 4, we selected the temporal separation of the metrology to avoid any risk of contaminating the signal of the target. Sweeping method b) and c) are difficult to adapt with this separation option. They would most likely require the indirect metrology approach which is less accurate because the laser beam does not go through the full system; it can’t account for beamsplitter or static mirror small movement and thermal deformation. The remaining option (step scan) present all advantages of static acquisition and will be easily integrated with the temporal separation of metrology.

From the point of view of the interferometer also, the step scan approach has the advantage of offering the ultimate flexibility in terms of positioning and dwell times offering infinite possibilities of non traditional sweep pattern such as uneven integration times or uneven sampling intervals.

9. RADIOMETRIC CALIBRATION STRATEGY

9.1 DESCRIPTION

Several strategies exist for radiometric calibration. The list includes in-flight calibration with internal calibration targets, pre-launch calibration on ground, and in-flight calibration using known celestial bodies.

Regardless of the calibration strategy used, the goal is always the same: to obtain the necessary information to convert the electric signal of the detector (integrated change, current or voltage) into equivalent radiometric units. The traditional method of calibration uses two measurements: one acquired while the instrument is looking at a target with a high energy flux (a "warm" target) and a second one while the instrument is looking at a target with a small energy flux (a "cold" target). For linear instrument, a straight line is then used between these two points (see Figure 12). The slope of that line for a given wavelength gives the gain of the instrument at that wavelength and the ordinate at the origin gives the offset of the instrument at that wavelength.

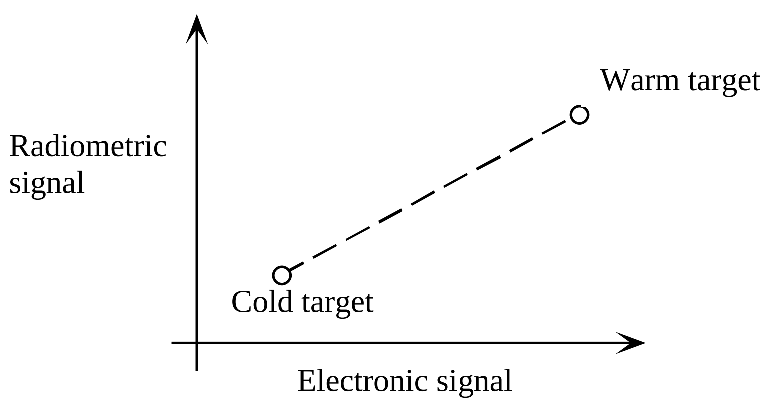


Figure 12: Two points calibration

The spectral gains, the spectral offsets and the exact calibration equation (including fine tuning such as non-linearity correction) can be determined on the ground, prior launch, in well controlled conditions. However, no matter how precise this preliminary calibration is, nothing guarantees that the instrument performance and response will remain the same after launch and through the lifetime of the instrument. Degradation of the optics and electronics, due to contamination, thermal stress, cosmic particles, exposure to ultraviolet radiation, etc. are likely to cause modifications that will affect the calibration. The most common source of radiometric calibration change are thermally induced gain and offset drifts. Detectors responsivity can change with operating temperatures. Thermal drift and spatial gradient can also affect the interferometric alignment which translates into change of modulation efficiency (visibility) or instrument responsivity. For the FTS operating in the thermal IR, the drift most frequently corrected for is the instrument self radiance, or the offset. On the other hand, for the NIR and visible, where the thermal emission is negligible, the offset may not be needed at all, only a measure of the response is required. Astronomers working on NGST requirements are asking for a radiometric accuracy on the order of a few percent on absolute flux measurements. Such a precision can be achieved on the ground but to maintain the accuracy after the launch, other calibration processes are likely to be required.

Calibration with internal calibration targets uses sources of controlled emission; blackbodies for infrared and lamps for the visible/near infrared. These targets are periodically inserted in the optical path at the entrance of the interferometer in order to monitor the evolution of the sensor and obtain calibration coefficients (spectral gains and offsets). They are usually used to illuminate uniformly the whole field of view so that the response of each individual pixel can be evaluated simultaneously and in the same conditions. However, such system cannot include the fore optics (the telescope) in the calibration process, as it would be impossible to insert a calibration target in front of NGST to illuminate uniformly the primary mirror. The response of the telescope is not necessarily constant since contamination due to outgassing and interplanetary dust can affect its spectral reflectance after the launch.

After launch, calibration information can also be obtained by observing celestial bodies with known and stable (over the lifetime of the instrument) spectral flux. This method relies on models and cross-referencing with other observatories. Since this calibration process includes the fore optics it can be used to monitor the evolution of the performance of the telescope. The major drawbacks of this method are that it will probably be necessary to reorient the telescope to point at the appropriate calibration targets and that these targets cannot cover the whole field of view. Another problem stems from the fact that such calibration processes depends on observations from the ground that include atmospheric effects, especially absorption in the infrared by water vapour, CO_2 and other molecules. This alters the accuracy with which the real spectrum is estimated.

There is a proposal that IFIRS only needs to be precise (repeatable) but not necessarily accurate (absolute). IFIRS could derive then its absolute accuracy from using known reference standards contained within the measurements. This approach is probably viable but requires some level of validation. For example the additional uncertainty introduced by the limited knowledge of the radiance of those standards.

However there exists a simple argument why there is negligible additional cost from hardware to provide absolute calibration sources as compared to allowing only relative calibration.

A relative calibration requires only stable reference sources, rather than known sources. In general, reference sources in the IR are bodies heated at a temperature suitably hot to provide enough photons in the spectral range used. A stable source thus requires its temperature to be monitored precisely and controlled accurately via heaters and/or coolers. At first sight the stability requirement does not imply knowing the source emissivity neither does it imply having a good emissivity. It is not the case however. By virtue of Kirchoff's law, a source with less than perfect emissivity also reflects the radiation from its surrounding in the instrument being calibrated. This situation generates additional requirements, albeit less stringent, on the knowledge of the temperature of the environment. Any change in the temperature of the environment around a grey but otherwise perfectly stable source translates into calibration errors.

The difficulty in assessing the temperature of the environment around a calibration source is great. Not only must the temperature of each surface in the field of view of the source be measured to some level of accuracy, but in the case where these surfaces are not perfectly black themselves (which is overwhelmingly so), the temperature of every surface in the field of view of these secondary surfaces must also be measured to some level of accuracy. In many cases these secondary surfaces cannot be black (for ex. a mirror) so that high order "scattering" must be considered.

For these reasons it is much simpler to work with a calibration source that does not reflect the environment, i.e. a blackbody with high emissivity. However a blackbody with high emissivity is also what is needed for achieving absolute calibration. The only extra work involved in achieving absolute calibration is that the temperature metrology must be absolute rather than relative – a relatively easy and straightforward task.

As for the telemetry, the heat source should be turned off during measurement. Cool down may take several hours/days.

9.2 COMPARISONS

Table 7: Qualitative comparison of various calibration strategies

Configuration	Advantages	Disadvantages
Pre-flight calibration / characterisation only	Simpler system design. Less expensive (no need for space qualified source) Less stringent weight, space, time and power requirement. Controlled environment.	Less reliable if used alone. Difficult to reproduce all space operating conditions. No capability to track instrument ageing.
In-flight calibration with internal calibration targets (blackbodies and lamps)	Ability to characterise and monitor the evolution of the individual response of the pixels of each array. Calibration can be optimised for target. Always available. No need to re-point the telescope. Accuracy of calibration over the entire FOV.	Complicates system design Requires calibration sources that generate heat in the system (risk of stray light contamination). Consumes power. Calibration does not include telescope fore optics.
In-flight calibration with astronomical references	Include fore optics. Simpler system design. Less expensive (no need for space qualified source) Weight, space, and power economy.	Satellite of telescope movement needed to point at calibration body. Availability of sources (2) within the pointing range of telescope may depend on spacecraft position. Only a few pixels at a time can be calibrated because the astronomical references do not cover the 3.3’ X 3.3’ FOV. Non-uniform calibration over all pixels, i.e. difficulties to find calibration source with uniform brightness. Cross-referencing with other observatories is required.

9.3 CONCLUSIONS

A combination of the three calibration strategies will likely be used for NGST. Each method has its own unique advantages and they fill out different tasks and purposes.

Pre-launch characterisation and calibration is always performed for testing purposes and to evaluate the sensor performance. It is performed in a controlled environment and is useful to evaluate the sensor parameters that affect the calibration, such as the non-linearity of the detectors, and that are more difficult to evaluate after launch.

On board calibration with tuneable blackbodies and lamps allows to monitor the evolution of the sensor response. The frequency of the calibration can be set according to the radiometric stability requirements, every two weeks for the gain and every couple hours for the offset. The internal calibration targets are always available without having to point the telescope and they can cover the whole field of view uniformly. Proper cooling and shielding should eliminate the risks of target signal contamination.

Calibration using celestial references can be used to verify the validity of calibration parameters obtained with the internal calibration targets. It is also useful to track the evolution of the onboard calibration targets and the fore optics. It is envisaged to perform such a measurement using on astronomical reference on a few pixels only. Using the on-board data, a fore optic (telescope) degradation variation can be inferred and applied to the whole array. Plus note that a body with known controlled emission will be needed for the interferometer second input port. These bodies tend to be blackbodies in the IR and light traps in the visible.

10.SUMMARY

In this section we present the baseline found for the NGST IFTS. We must remind the reader that this work is first and foremost motivated by the desire to derive an IFTS baseline for the purpose of *cost and schedule estimates*. These trades are only indicative of the type of studies the designers will conduct during the development of this sophisticated spectrometer module. In fact, when a doubt existed, the choice was motivated by spectrometric performance in the first place, before cost, practicality or maturity of the technology. This may have led to a technical baseline that is more complex and ambitious than usually encountered.

The resulting baseline is illustrated schematically in Figure 13.

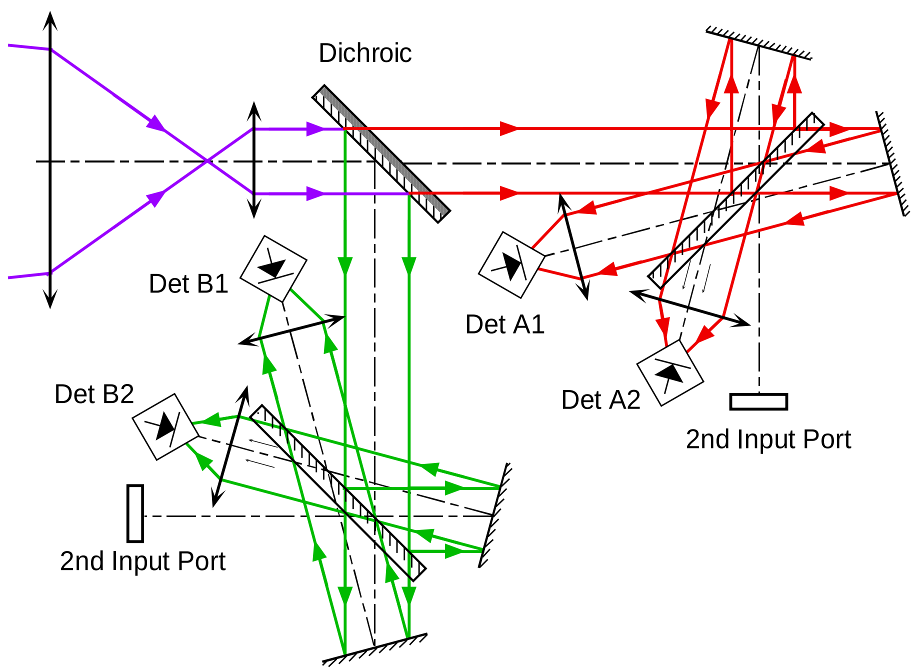


Figure 13: Baseline NGST IFTS

This instrument has the following characteristics.

- Flat mirror system (higher efficiency)
- Four port design (higher efficiency)
- Temporally separated metrology with dynamic alignment and possible hybrid system (no contamination, no obscuration)
- NIR or VIS laser diode.
- Dichroic at the input with multiple interferometers (optimised performance over broad spectrum, higher efficiency than a single interferometer).
- The system performs the sweep using the step scan approach

11.ANNEX

11.1 ANNEX A: ESTIMATION OF AMOUNT OF STRAY LIGHT FROM THE METROLOGY

We here only consider the stray light that is due to multi-reflections in the beamsplitter. Scattering by particles in the optical path, scattering on reflective optical surfaces, scattering within optical components and diffraction effects are not considered. Figure 14 is schematics of the multi-reflections in a beamsplitter. The calculations are based on the figure. Only the beams that exit the beamsplitter toward the primary output port (i.e. at the bottom of the figure) are considered. These beams are given a number that corresponds to the order of scattering. Order 0 is the main beam. Positive number are for "ghost" beams that are reflected only once by the interferometer mirror (exiting at the left of the main beam on the figure) and negative numbers for "ghost" beam that have been reflected twice by a mirror (exiting at the right of the main beam on the figure).

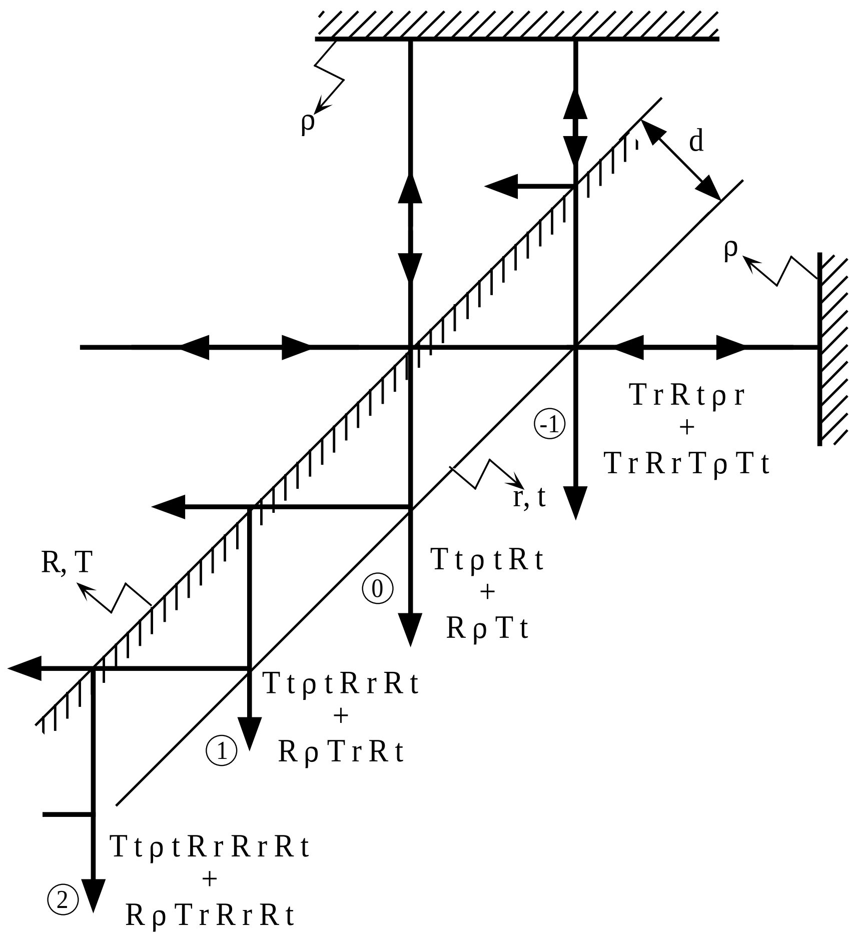


Figure 14: Schematics of the multi-scattering in the beam-splitter

For an incidence angle of 45º, the reflectance and transmittance at the first surface of the beamsplitter are, respectively, R and T. At the second interface they are, r and t. The reflectance of both mirrors at an incidence angle of 0º, is ρ. The fraction of radiation exiting the beamsplitter toward the output port after N reflections in the beamsplitter is:

$$R\,T\,t\,\rho\,(r\,R)^{N}\,(t+1) \qquad \text{for } N>0$$

$$T\,r^{2}\,R\,(r\,R)^{-(N+1)}\,\rho\,t\,(1+T) \quad \text{for } N<0$$

and the Nth reflection exits the beamsplitter at a distance $\sqrt{2}\,|N|$ d from the centre of the beamsplitter (assuming the incoming beam hits the beamsplitter in the centre), where d is the thickness of the beamsplitter.

Let's suppose a circular beamsplitter with a diameter of 10 cm and central metrology mirror of 3 cm, corresponding to an obscuration of about 10%. The metrology mirror will only "catch" the light that exits within a radius of 1.5 cm from the centre of the beamsplitter. For a particularly thin beamsplitter of 5 mm of thickness, only the light from the first two multi-reflections (N=-2,-1,1 and 2) will be blocked by the metrology mirror, the other "metrology ghosts" will reach the detector.

Assuming that we have a very good beamsplitter and the following values for the reflectances and transmittances:

$R = 0.5$

$T = 0.5$

$r = 0.01$

$t = 0.99$

$\rho = 0.98$

the total fraction of the incoming metrology signal reaching the detector because of multi-reflections in the beamsplitter is:

$$R\,T\,t\,\rho\,(t+1)\sum_{N=3}^{14}\left[(r\,R)^{N}\right]+T\,r^{2}\,R\,\rho\,t\,(1+T)\sum_{N=-3}^{-14}(r\,R)^{-(N+1)}$$

or about 6×10^{-8}. For a laser with a wavelength of 850 nm and a power of 1 mW, this fraction represents about 3×10^{8} photons/s. To compute this value a nearly-perfect beamsplitter was used and several other causes of scattering (surface scattering, volume scattering, scattering by particles in the optical path, etc.) have been neglected. For these reasons, the value obtained should be regarded as a minimal value.

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